PB87-191508

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Southern Research Inst., Birmingham, AL

Prepared for

Environmental Monitoring Systems Lab.
Research Triangle Park, NC

May 87

U.S. Department of Commerce
National Technical Information Service
NTIS

PB87-191508

EPA/600/D-87/167
May 1987

EFFECTS OF SAMPLING NOZZLES ON THE PARTICLE COLLECTION CHARACTERISTICS OF INERTIAL SIZING DEVICES

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CR812274

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U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NC 27711

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/D-87/167		

4. TITLE AND SUBTITLE	5. REPORT DATE
Effects of Sampling Nozzles on the Particle Collection Characteristics of Inertial Sizing Devices	May 1987
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
A. D. Williamson, W. E. Farthing, T. E. Ward, M. R. Midgett	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Southern Research Institute 2000 Ninth Avenue, South Birmingham, Alabama 35255-5305	11. CONTRACT/GRANT NO. CR-812274

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
U. S. Environmental Protection Agency Office of Research and Development Environmental Monitoring Systems Laboratory-RTP Research Triangle Park, NC 27711	Final
	14. SPONSORING AGENCY CODE EPA/600/08

15. SUPPLEMENTARY NOTES

16. ABSTRACT

In several particle-sizing samplers, the sample extraction nozzle is necessarily closely coupled to the first inertial sizing stage. Devices of this type include small sampling cyclones, right angle impactor precollectors for in-stack impactors, and the first impaction stage of several cascade impactors. The closely-coupled nozzle of these samplers may affect the flow profile of the incoming sample gas stream enough to perturb the paticle collection characteristics of the sizing stage. Since this perturbation is in itself an inertial size-dependent separation, the effect is expected to be more significant for higher inlet velocity, smaller nozzle diameter, and larger characteristic D_{50} of the first sizing stage. In a recent laboratory study of a stack sampling cyclone with various sampling nozzles, significant perturbations were observed in the actual D_{50} when some of the nozzles were used. Some nozzles caused the D_{50} of the cyclone to be reduced from 10 μm to less than 6 μm. Several alternate nozzle designs were considered to alleviate this behavior. Simple extension of the nozzle length was sufficient to restore the 10 μm sampler D_{50}, but at the expense of enhanced deposition of the test aerosol particles on the nozzle walls.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Emission Measurement, Particle Sizing Stationary Source Particle Size Measurement Source Emission Measurement Particle Sizing Pollution Measurement, Particle Sizing Particle Sizing, Stationary Sources		

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to public	Unclassified	18
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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INTRODUCTION

In several particle-sizing samplers for stack sampling applications, the sample extraction nozzle is of necessity closely coupled with the first inertial sizing stage. That is, there is a relatively short gas flow path between the nozzle entry point and the region of significance for inertial separation of particles of the first stage. Devices of this type include small sampling cyclones, right angle impactor precollectors for instack cascade impactors, and the first impaction stage of several cascade impactors. The closely-coupled nozzle of these samplers may affect the flow profile of the incoming sample gas stream enough to perturb the particle collection characteristics of the sizing stage immediately downstream. Since this perturbation is in itself an inertial size-dependent separation, the effect is expected to be more significant for higher inlet velocity, smaller nozzle diameter, and larger characteristic D_{50} of the first sizing stage.

The potential for this effect has been almost universally ignored by users of particle sizing devices. However, in a recent laboratory study of a stack sampling cyclone with various sampling nozzles, significant perturbations were observed in the actual D_{50} when some nozzles were used. This paper describes our experiments and their results, along with our interpretation of the cause and magnitude of this effect and possible solutions to the problem represented by it.

This study arose as an outgrowth of an EPA research program to develop stationary source sampling methods for particulate matter nominally smaller than 10 μm aerodynamic diameter (designated PM_{10}). The sizing device chosen as a candidate PM_{10} inertial separator was the first cyclone of the Southern Research Institute/EPA Five-Stage Series Cyclone Train[1], designated Cyclone I. This cyclone, when operated at an appropriate flowrate determined by the stack gas conditions, has been demonstrated to have an inherent 50 percent collection diameter (D_{50}) of 10 μm. The purpose of this study was to determine whether the 10 μm D_{50} was perturbed by inertial effects resulting from nozzle extraction from high velocity gas streams. After such perturbation was in fact discovered, considerable effort was applied to determine the best ways to minimize the effect, which may represent a significant problem in some sampling situations. These attempts which are also partially described in this paper, included design and further testing with modified nozzles.

EXPERIMENTAL METHODS

Apparatus

The cyclone was challenged with monodisperse ammonium fluorescein aerosol particles generated by a vibrating orifice aerosol generator (VOAG) of the design of Berglund and Liu[2]. The VOAG operational and aerosol recovery procedure are described in more detail in Smith, et. al.[1] The VOAG provided monodisperse dye aerosol of selected particle size at a rate of about 60,000/sec. After lofting and drying with air the aerosol is passed through the sampler with an absolute filter at its exit. After the sampling run, all internal surfaces of the sampler and the filter are carefully washed with a

measured volume of solvent. Spectrometry or fluorometry then determine the concentration of dye in the wash solutions and thus the collected aerosol mass for each surface and that passing to the backup filter. To avoid effects of particle charge which occurs during generation of the aerosol, a Kr-85 radioactive source is installed as a charge neutralizer at the top of the VOAG drying column.

To simulate sampling from process streams, an apparatus was constructed to establish a flowstream substantially larger than the nozzles with a uniform velocity profile at (or near) the nozzle inlet and minimum dilution of the test aerosol. The apparatus is illustrated in Figure 1 with the VOAG at the bottom and Cyclone I and filter in the main flowstream near the top. Aerosol leaves the VOAG drying column through a 3/8 inch tube at the center of the main flowstream. This monodisperse aerosol combines with the main flow (make-up air) which is drawn through the air filter and plexiglass tube (1.5 inch diameter) by the hi-vol blower at upper left. This flowstream with aerosol near the center, along its axis, then passes into the 3.5 inch diameter plexiglass tube before encountering the nozzle of Cyclone I. The blower can be adjusted to establish the desired velocity at the nozzle which matches the "plug flow" velocity corresponding to the cyclone flowrate and nozzle inlet diameter. The gas velocity is measured at the ports shown, 1.5 inches upstream of the nozzle for this adjustment. The velocity profiles were found to be uniform in the central portion where the nozzle is located and outward to 1/2 inch radius, well beyond the edge of any nozzles tested.

Introduction of the VOAG aerosol at the center of the main flow while limiting the distance over which turbulent mixing occurs reduces dilution of the aerosol. Most of the particles remain near the center of the main flow stream where it enters the cyclone nozzle. This was verified during construction of the apparatus by passing small, helium-filled bubbles through the VOAG drying column to view the center portion of the flowstream. This feature kept run times necessary to sample sufficient mass of dye particles to about an hour.

Gas not sampled by the Cyclone I passes through an 8 x 10 inch filter and then to the blower. A small portion (1/4 cfm) was drawn off into an optical particle counter, shown at upper right of Figure 1, to monitor the aerosol during each run. Plumbing was also available to divert the VOAG aerosol directly to the optical particle counter.

Procedure

Experiments were performed holding the flowrate of the cyclone constant while varying the particle size from run to run. All runs were performed at laboratory temperature 75° to 80°F and with ammonium fluorescein particles. The cyclone was operated at a sample flow rate of 0.45 actual cubic feet per minute, corresponding to a 10 μm cutpoint. Prior to starting a run, the cyclone was leak checked and installed and the sample control box adjusted to the desired flow value(s). Then a calibrated pitot or hot wire anemometer was inserted in front of the nozzle for blower adjustment. The VOAG aerosol was diverted to the optical particle counter during this preparation. After these

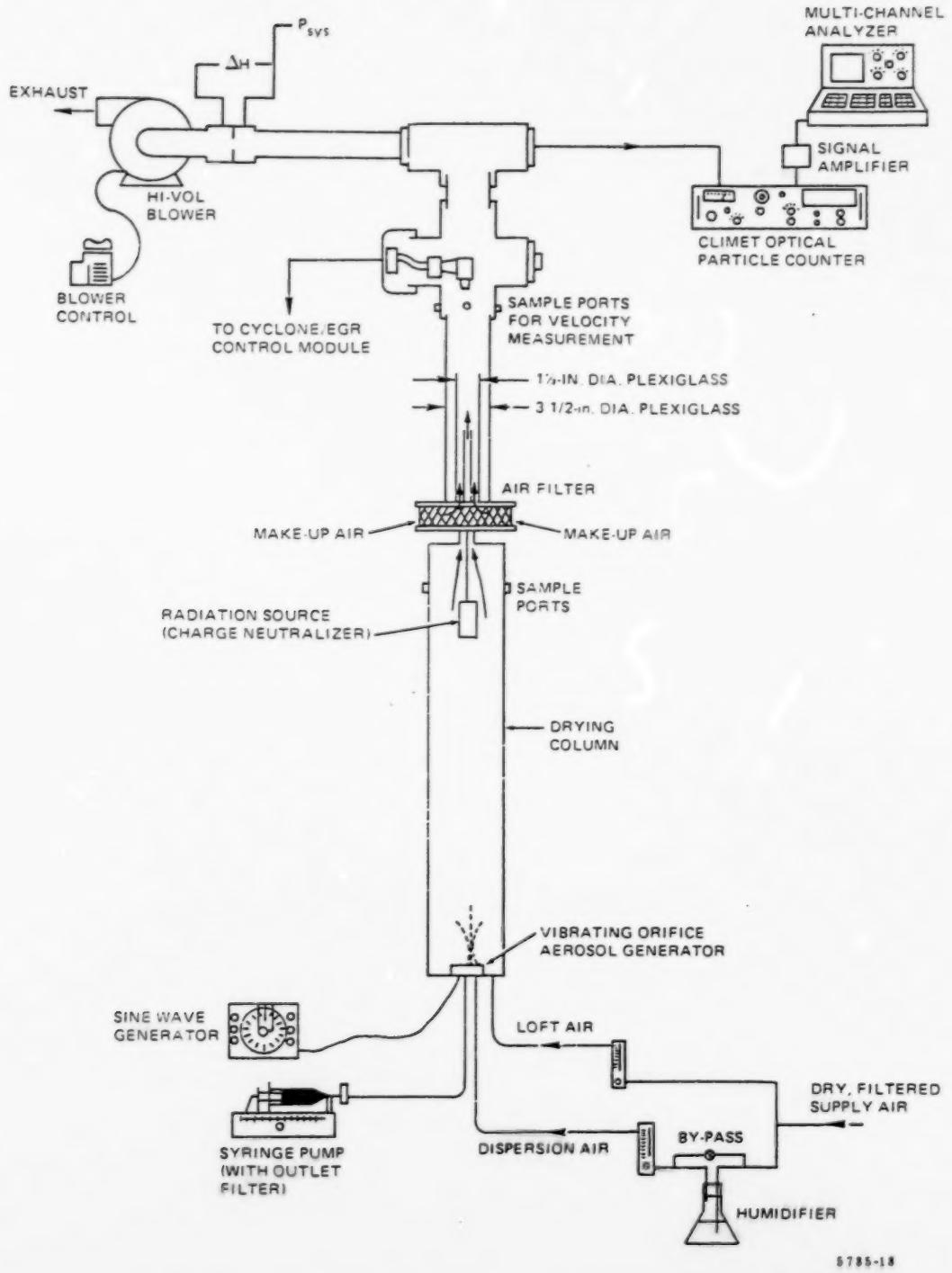

Figure 1. Isokinetic cyclone test apparatus.

initial adjustments, the control box was turned off and the VOAG aerosol was checked for desired size and monodispersity with the optical particle counter and a filter sample which was observed with a microscope. Immediately after connecting the VOAG output to the main flowstream the run was begun, gas velocity checked, and the pitot removed. Stability of the blower flowrate was monitored during the run with the downstream orifice shown in Figure 1. After the run checks of the VOAG aerosol were again performed, and photomicrographs of particles generated before and after the run were obtained.

For most runs, five different interior surfaces of the sampler were washed separately with 2% ammonium hydroxide solution to characterize behavior. These were the nozzle, the cyclone body and cup, the cap through which the gas exits the cyclone, the exit tube, and the filter and its holder. In some runs nozzles were washed in separate portions to identify how deposits varied along its length. This wash accomplished by successive dippings of the nozzles into separate test tubes, each dip washing successively more of the nozzle.

A Bausch and Lomb Spectronic 88 spectrometer and a G.K. Turner III fluorometer, both calibrated with current dye samples, were used to measure concentration of wash solutions. The mass collected, percent of the total collected mass, and collection efficiency of each surface were calculated. Total mass collected ranged between 50 and 1000 μg or 10^6 to 10^7 particles. The collection efficiency of a surface is defined as the ratio of the mass collected by the surface to the mass collected by it and all surfaces downstream of it.

Nozzles Tested

The cyclone nozzles used in this study are schematically depicted in Figure 2. The top nozzle in the figure, used as a reference throughout this study has a nominal 0.5 in. (12 mm) inside diameter corresponding to the size of the cyclone inlet. This nozzle and the second nozzle in the figure are part of the nozzle set designed by Southern Research and available from commercial vendors. The second nozzle type has an internal expansion angle of 20° (10° half-angle) which follows a section of straight internal bore. Two nozzles, with diameters 0.235 and 0.195 in., were used. The third nozzle, with a longer straight section and a more abrupt (50° full angle) expansion, was constructed in our shop for possible use in one of the field studies in the current PM_{10} program. Two nozzles of this type (diameters 0.155 and 0.138 in.) were studied.

The bottom three nozzles in Figure 2 were fabricated during the course of these studies in an attempt to mitigate the effects found in the smaller nozzles studied. The first of these nozzles had essentially no initial straight bore section and a very gentle 7° internal expansion full angle. The second was the same length as the first, but had a 14° initial expansion to the 0.5 in. cyclone inlet diameter followed by a straight bore section. Nozzles of these geometries having of 0.125 and 0.16 in. inlet diameter were constructed. The bottom nozzle type geometry has an abrupt (90° full angle) expansion followed by a straight bore section of variable length. The nozzle

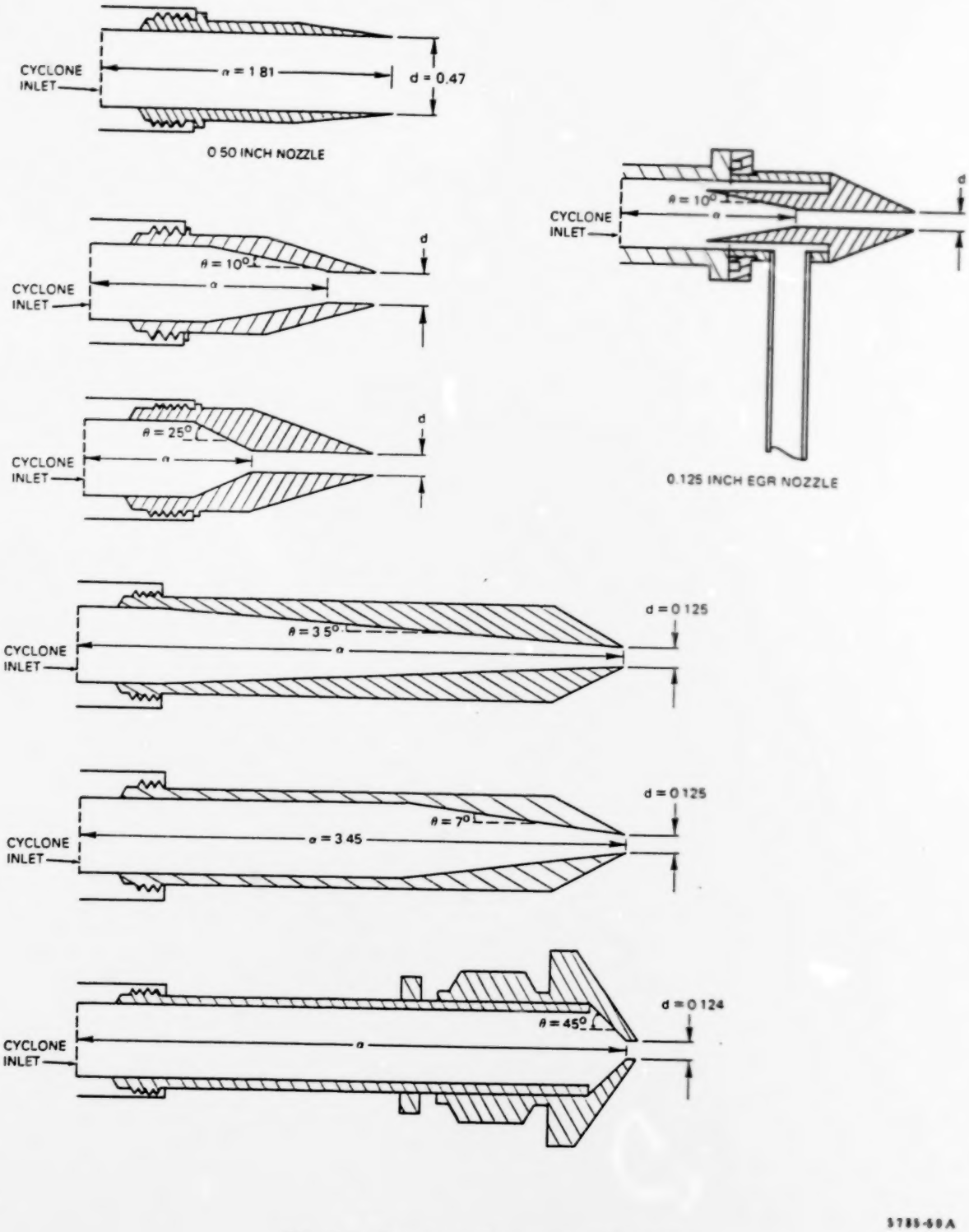

Figure 2. Geometry of cyclone nozzles tested.

on the right is designed to be used with Cyclone I as part of the Emission Gas Recycle (EGR) sampling train.[3] The results of testing with EGR nozzles will be presented elsewhere, but for this study a small amount of these data are presented in which no recycle air is added to the recycle tube which extends vertically from the side of the nozzle in the figure. Without recycle air, this nozzle represents a different geometry of abrupt expansion nozzle.

RESULTS

Figure 3 presents the collection efficiency as a function of particle diameter of Cyclone I using the nominal 0.5 in. nozzle shown at the top of Figure 2. For this test and all others in this study, the cyclone was operated isokinetically at ambient temperature at a flowrate of 0.45 acfm. This corresponds to a duct and nozzle inlet gas velocity of 6.2 ft/s. The cyclone efficiency (defined as the fraction of particles passing through the nozzle and entering the cyclone which were actually collected there) shows a familiar sigmoidal functional form with a 50% collection diameter of 10 μm. Also plotted as diamonds on Figure 3 are the collection efficiencies of the inner surface of the 0.5 in. nozzle for the same sample runs. The data in Figure 3 can be taken as nearly ideal behavior for the cyclone and nozzle and are used as a reference against which data using all the other nozzles are compared.

Tapered Nozzles: Original Nozzle Set

The results of tests using the two commercial nozzles with intermediate (0.235 and 0.195 in.) inlet diameter and modest (20°) internal expansion angle are shown in Figure 4. Figure 4A gives cyclone efficiencies. Except for the reproduction of the reference nozzle curve, the curves on Figures 4-7 are the results of a French curve fit of the appropriate data points. The behavior of Cyclone I appears to be slightly different than with the 1/2 in. reference nozzle, but the cut size is changed by much less than 1 μm. However, Figure 4B, giving the nozzle efficiencies corresponding to Figure 4A, shows significant nozzle losses. The larger nozzle had losses increasing with particle size from 3% (at 4μm) to about 20% (at 10 μm). With the smaller nozzle, losses decreased only slightly for smaller sizes.

Nozzles With Large Expansion Angle

Figure 5A gives cyclone collection efficiency with nozzles having abrupt expansions; i.e. large expansion angles, inlet diameters of 0.155 in. and 0.138 in. Three EGR nozzles with zero recycle air are also included in this group since they also present an abrupt expansion to the flow at the end of the sample tube. The cyclone cut diameter was shifted down to about 6 μm with all of these nozzles. The magnitude of the difference between the reference curve and all of the data points shown is far outside the range of expected random variation. Although more data is needed for confidence, it appears that the 0.138 in. nozzle caused the lowest cut while the 1/4 in. EGR nozzle gave the largest cut of this group. Figure 5B gives the nozzle efficiency for this group. The highest losses were incurred by the 0.138 in., 30% at 4 μm decreasing to 20% at 10 μm. The 0.155 in. nozzle had about 10% at 4 μm and 15%

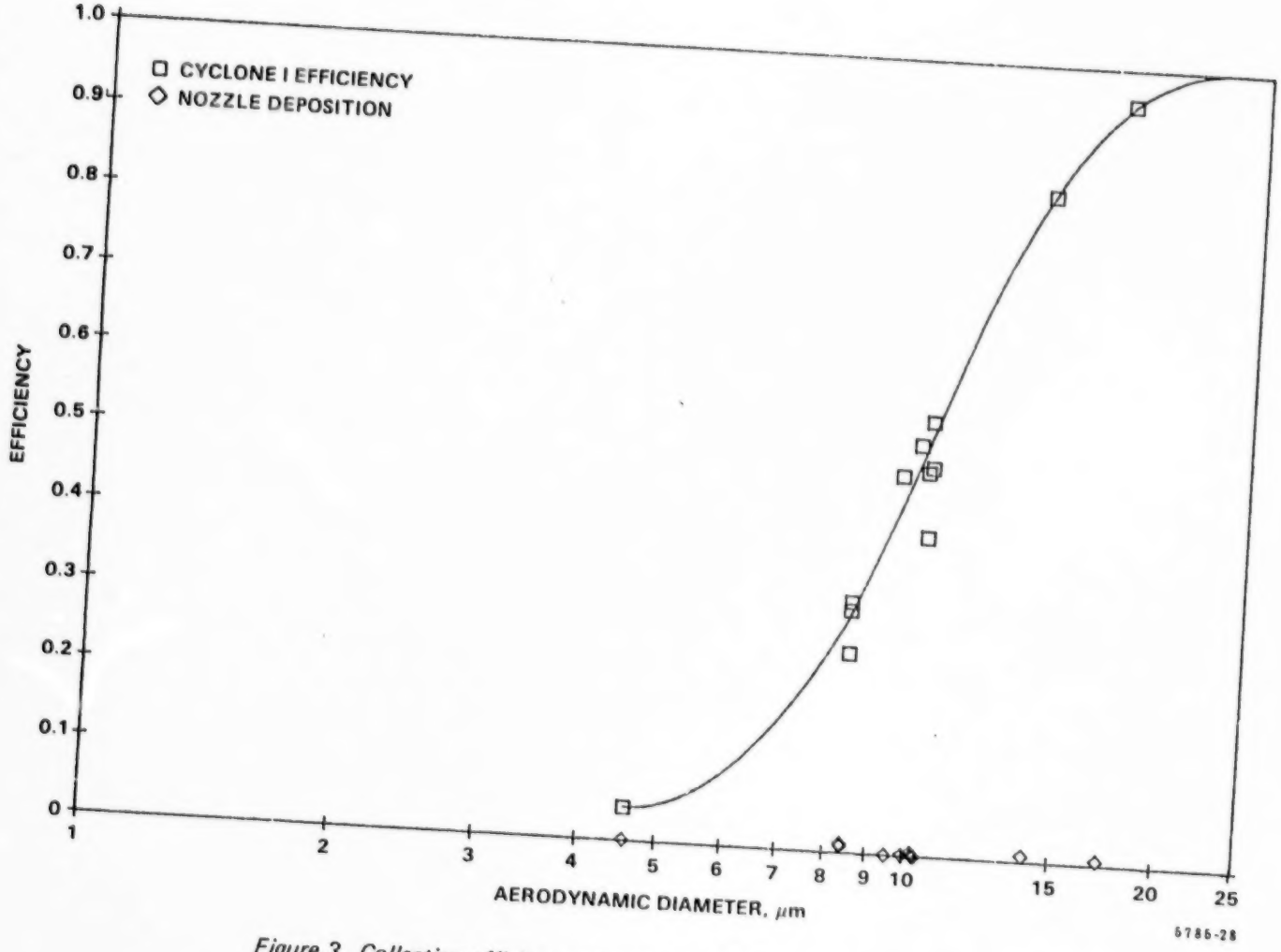

Figure 3. Collection efficiency of cyclone and reference 1/2-in. nozzle.

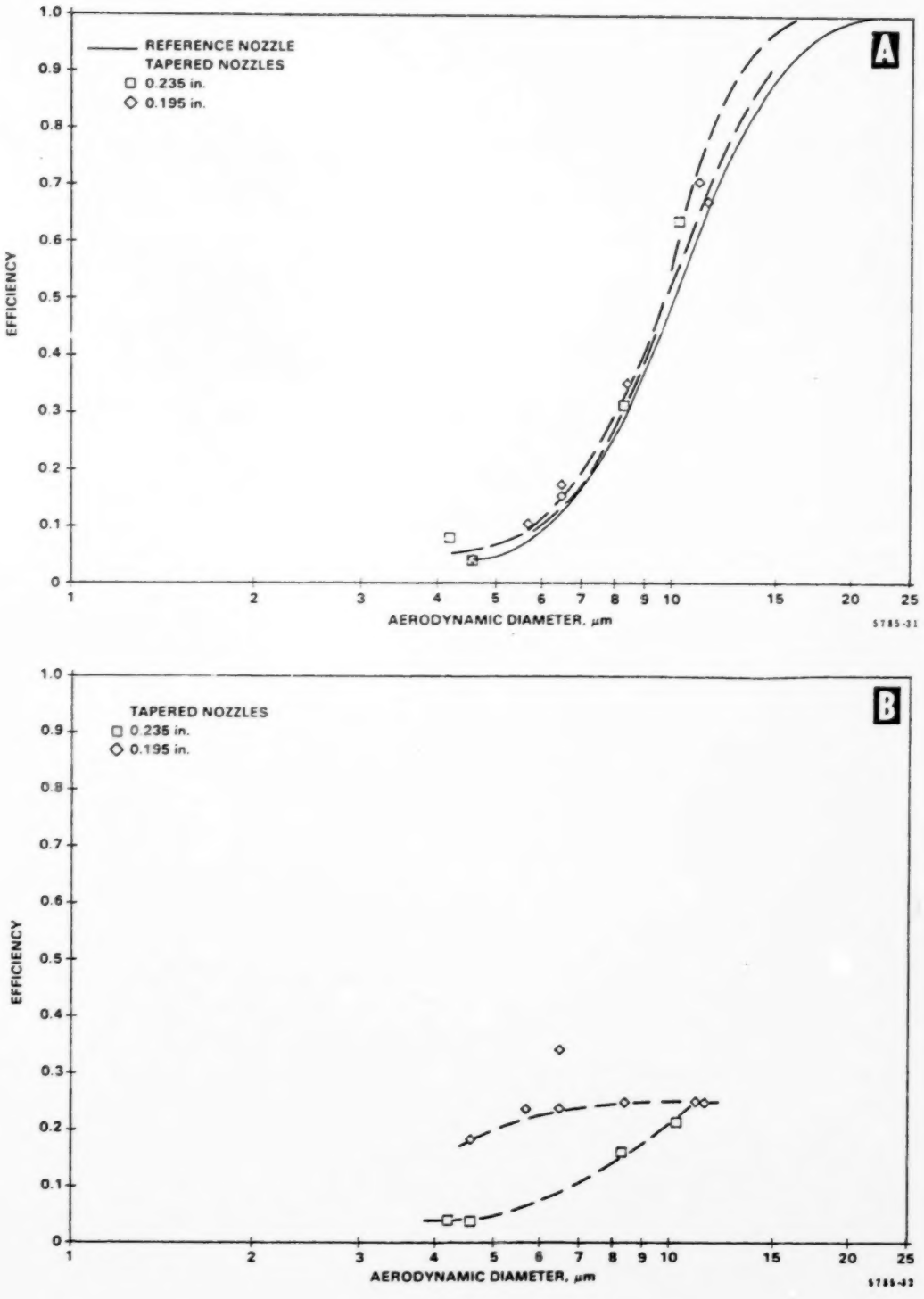

Figure 4. Collection efficiency of cyclone (A) and of nozzles (B) when original tapered nozzles are used.

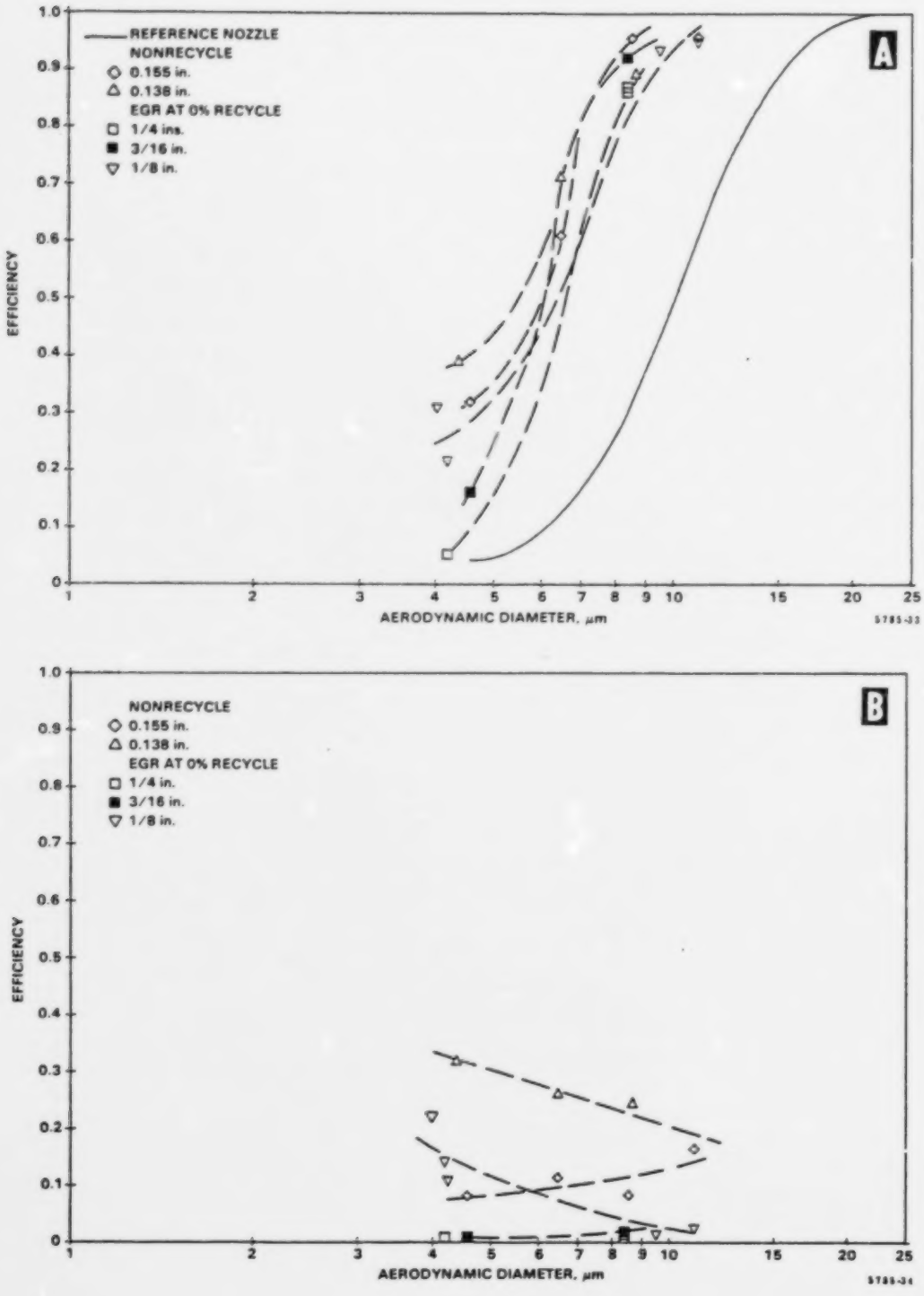

Figure 5. Collection efficiency of cyclone (A) and of nozzles (B) when nozzles having large internal expansion angle are used.

at 10 μm. With the 1/8 in. EGR nozzle the losses around 4 μm (10-20%) appear much higher than at 10 μm (1%). The losses for the 2 larger EGR nozzles were insignificant.

Modifications of Nozzles

Further measurements were performed to test approaches for eliminating the observed shift in cyclone cut size at the higher nozzle inlet velocities. The results obtained with the original nozzles indicated that the inertia of the higher velocity aerosol streams was not dissipated sufficiently to prevent impaction in the cyclone. Therefore, modifications were tested which appeared likely to reduce the sample gas velocity prior to entering the cyclone. Two types of nozzles were tested. One group had large expansion angles while the other group had small expansion angles, 7° and 14°. The first large expansion angle nozzle was made initially by installing a cap with a 0.125 in. hole in the center over the standard 1/2 in. nozzle. Sampling a monodisperse aerosol with it gave a lower collection efficiency for 8 μm particles than with the 1/8 in. EGR nozzle at 0% recycle or with the 0.138 in. nonrecycle nozzle. Thus, two longer nozzles having the geometry of the bottom nozzle in Figure 2 were also fabricated and tested. Another large angle nozzle of added length was constructed by adding a simple extension to the 0.125 in. EGR nozzle. The 7° and 14° nozzles shown above the bottom nozzle in Figure 2 were cast from epoxy resin. To insure that effects of particle charge were not present a conductive paint was applied.

Results Using Large Expansion Nozzles with Varied Length

Figure 6A gives measured cyclone efficiencies with the 1/8 in. nozzles having large expansion angles, including the EGR nozzle at 0% recycle rate. The cyclone efficiencies decreased to that with the reference nozzle when the expansion distance was 2.2 in. and greater. Figure 6B presents the nozzle efficiencies corresponding to Figure 6A. These modified nozzles had substantially higher nozzle losses than the unextended EGR nozzles. Of the nonrecycle nozzles which did not effect cyclone behavior (2.2 and 3.1 in. expansion distance) the shorter one exhibited lower nozzle loss at 8 μm. The extended EGR nozzle with expansion distance of 3.1 (which did not affect cyclone behavior) exhibited nozzle losses of 20% at 4 μm and 35% at 8 μm. Apparently the initial smaller expansion angle of the EGR nozzle contributed to reduction of nozzle loss.

Results with Nozzles of Varied Internal Expansion Angles

Figure 7A presents measured cyclone efficiency for the tapered nozzles compared to nozzles having large expansion angles and the same inlet diameter. Original nozzles (0.235 in. and 0.195 in.) with small expansion angles are included in this figure with the modified tapered nozzles. Looking first at the 0.16 in. nozzle (with 7° angle) and the 0.154 in. nozzle (with 50° angle) one sees that the effect on cyclone behavior exhibited by the original nozzle is absent with the modified 7° nozzle. Cyclone behavior was not affected by any of the three 1/8 in. nozzles; one with an expansion distance of 3.1 in. and an abrupt expansion, and the other two with expansion distance of 3.2 in. and

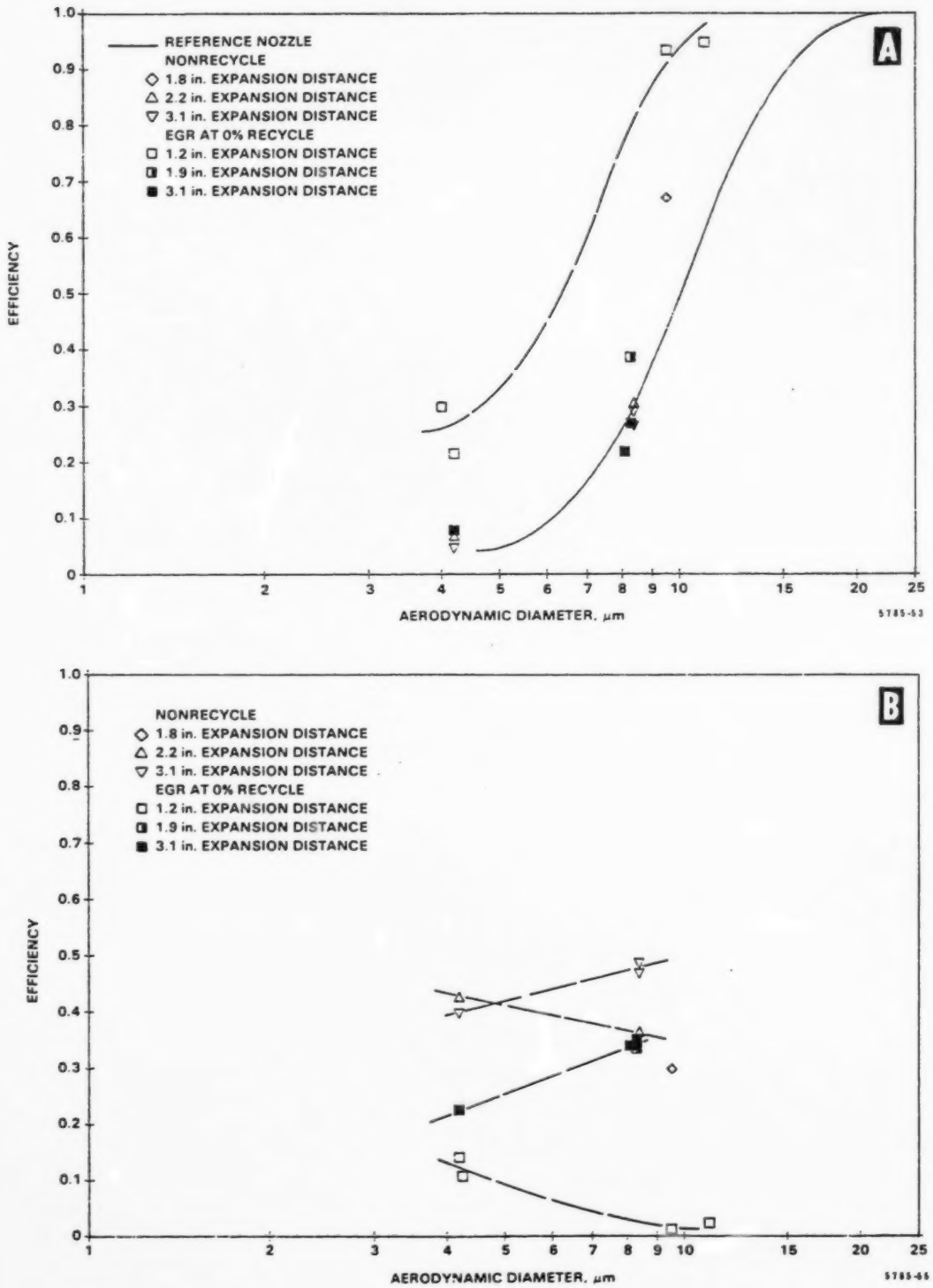

Figure 6. Collection efficiency of cyclone (A) and of nozzles (B) when 0.125-in. nozzles of varying lengths having large expansion angles are used.

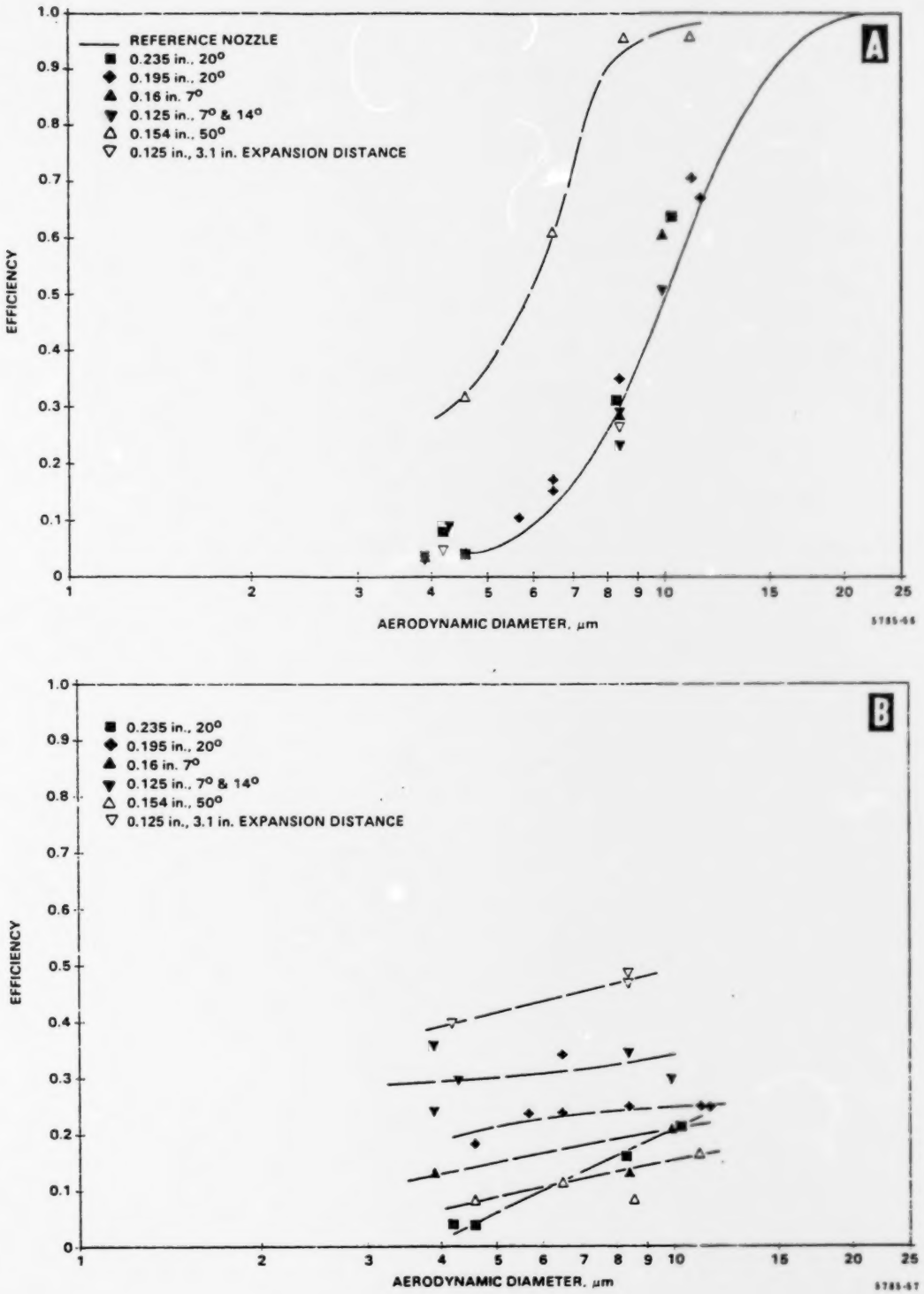

Figure 7. Collection efficiency of cyclone (A) and of nozzles (B) when nozzles of varying internal expansion angles are used.

tapered at 7° and 14° respectively. Figure 7B presents nozzle losses corresponding to cyclone efficiencies in these tests. Considering first the 0.16 in. and 0.154 in. nozzles one sees that the tapered nozzle (which does not affect cyclone behavior) exhibited about 5% higher nozzle loss. This 0.16 in. tapered (7°) nozzle had losses about 5% lower than the 0.235 in. nozzle with a 20° expansion angle. Of the three 1/8 in. nozzles (7° and 14° compared to 90° expansion angles) the tapered nozzles had 10% to 15% lower losses (30% compared to 45%).

CONCLUSIONS

The data in Figures 4-7 show two effects which are less than ideal. The cyclone D_{50} was lowered using many of the nozzles; for some nozzles the D_{50} was reduced to under 6 μm. The second effect was a tendency for the nozzle rather than the cyclone to collect the incoming aerosol. In field sampling, much of the collected particulate might be expected to "blow off" as agglomerated and be collected in the cyclone. For a given geometry, both of these effects increased as the nozzle diameter was decreased to correspond with increased duct velocity. The practical impact of both effects on field sampling is to cause particles smaller than the calculated cyclone D_{50} to be collected, giving the appearance of a larger mean aerosol size than is present in reality. For PM_{10} applications, the effect is to cause a low bias in apparent PM_{10} concentrations.

The cause of the shift in D_{50} associated with some nozzles appears to be high inertia associated with high velocity gas streams. The shift in D_{50} was found throughout the data to correlate closely with the velocity of the gas entering the nozzle. A quantitative description of the collection of particles in cyclones is beyond the scope of this study. However, it is obvious that values of the impaction parameter, $\sqrt{Stk}$, referenced to the nozzle inlet are higher with smaller nozzle diameter (required for higher direct velocities) than with the reference nozzle (with corresponding lower gas velocity). Thus impaction in the cyclone was enhanced by the higher gas velocities entering the cyclone.

Obviously, this problem is eliminated by causing the sample gas to decelerate after entering the nozzle. Extending the nozzle inlet farther from the cyclone inlet regained the basic cyclone performance. However, nozzle losses were enhanced in most instances. This is illustrated in Figure 8 where nozzle losses are plotted versus nozzle inlet velocity for different groups of nozzles. One group is the original nozzles which affected cyclone behavior. These nozzle losses are less than 10% except for the 0.155 in. and 0.138 nozzles (shown as open triangles at 58 and 76 ft/sec in Figure 8) which had abrupt expansion from the inlet diameter to the 0.5 in. exit diameter. The other data in this figure show losses for nozzles of several geometries which did not effect cyclone behavior. The lowest losses occurred for tapered nozzles with expansion angles of 7° or 14°. These differences in losses between nozzle geometries were probably caused by flow separation accompanied by a region of flow recirculation with the larger expansion angles.

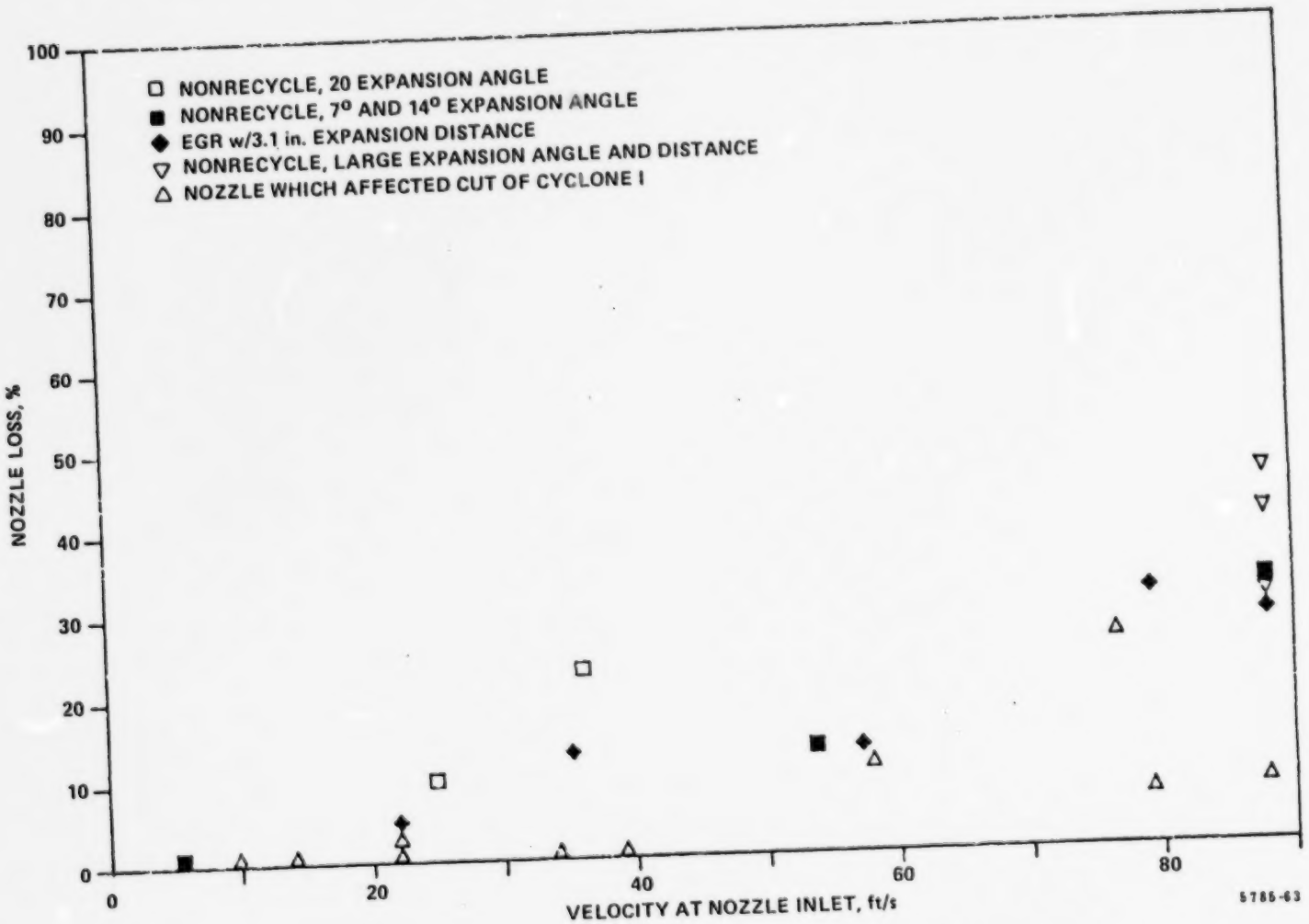

Figure 8. Summary of nozzle losses for nozzles used in these tests when operated isokinetically at designated cyclone flow rate.

These laboratory data show that nozzles for Cyclone I should be redesigned with a smooth taper from the nozzle inlet diameter to the 0.5 in. diameter of the cyclone inlet. This type of design appears to allow sufficient gas expansion within the nozzle to restore the collection performance observed at lower velocities. However, the data obtained for this as well as other redesigned geometries tested thus far indicate that nozzle losses will be significant for the small diameter nozzles required for use at high stream velocities. For particulate diameters within the range studied here (4 to 10μm) losses would increase from 1% at 5 ft/sec to about 10% at 30 to 60 ft/sec, and to 30% above 80 ft/sec (see Figure 8, closed symbols). This investigation of nozzle modifications used nozzles whose lengths at high stream velocities would require ports larger than 4 in. diameter. At this point it is not certain whether shorter nozzles can be designed with suitable performance characteristics.

Current work is in progress with redesigned nozzles which appear to show improved performance. However, these results indicate that caution should be used when interpreting size distribution measurements involving the first collection stage of samplers which use closely coupled nozzles such as other cyclones, cascade impactors, or right-angle inertial preseparators for stack sampling. There is every reason to expect that these samplers will also show the effects observed in this study.

ACKNOWLEDGEMENT

Funding for this project was provided wholly or in part by the Environmental Protective Agency under cooperative agreement CR-812274 with Southern Research Institute. It has been subject to the Agency's review, and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

REFERENCES

1. Smith, W.B., D.B. Harris, and R.R. Wilson, Jr., "A Five-Stage Cyclone System for In Situ Sampling". Environ. Sci. and Technol., 13(11):1387, 1979.

2. Berglund, R.N., and R.Y.H. Liu, "Generation of Monodisperse Aerosol Standards". Environ. Sci. Technol., 7(2): 147 (1973).

3. Williamson, A.D., R.S. Martin, D.B. Harris, and T.E. Ward, "Design and Characterization of an Isokinetic Sampling Train for Particle Size Measurements Using Emission Gas Recycle". JAPCA, 37:249 (1987).